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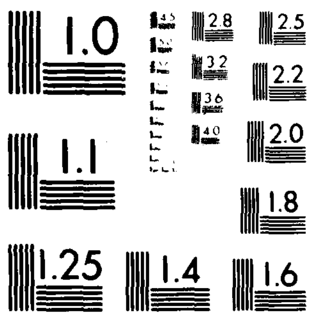

MICROCOPY RESOLUTION TEST CHART

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THE EFFECTS OF CONTROL SYSTEM AND DISPLAY VARIATIONS FOR AN ATTACK HELICOPTER MISSION THROUGH PILOTED SIMULATION

EDWIN W. AIKEN
AEROMECHANICS LABORATORY
U.S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA 94035

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Research into methods by which highly maneuverable advanced helicopters can be made to function – with reasonable pilot workload levels – as stable platforms for target designation and/or weapon delivery at night and in adverse weather is a major interest of the U.S. Army Aeromechanics Laboratory. Two candidate techniques under investigation are: (1) helicopter control system modifications that alter the aircraft's response to pilot control inputs and to external inputs such as turbulence and (2) variations in the methods by which critical information is displayed to the pilot in an attempt to reduce the effort required to interpret and respond to a given situation while still maintaining a satisfactory level of system performance. In support of this research, a piloted simulator experiment was designed and conducted to assess the effects on overall system performance and pilot workload of variations in control system characteristics and display format and logic for a nighttime attack helicopter mission. This paper describes the experiment and presents major results and conclusions.

BACKGROUND

The requirement that VTOL aircraft operations be conducted at night and under conditions of limited visibility has given impetus to research that is best understood by reference to the pilot-controlled vehicle-display system depicted in figure 1. This figure defines the elements of the system; when integrated, these elements determine the pilot workload necessary to achieve a given level of system performance.

The pilot's effort comprises three elements: (1) the mental workload required to collect the required information from sources such as motion and visual cues; (2) the decision-making process based on this information; and (3) the physical workload, such as control motions, required to perform the task. The pilot's task in this experiment demands a high level of mental effort because of the requirement to stabilize and control the aircraft in several axes simultaneously with limited visual cues while searching for and acquiring a target under hostile conditions.

In attempts to reduce pilot effort without significantly degrading overall system performance, the system designer must address the characteristics of the controlled vehicle and of the pilot's display. That is, given the characteristics of the unaugmented aircraft and the particulars of its environment,

system performance, as a function of pilot effort, is determined by (1) the stability and control augmentation system (SCAS) and (2) the display format and logic.

Control/display research, both generic and specific in nature, has been applied to particular VTOL aircraft tasks; reference 1 presents a survey of the results of such investigations of the helicopter decelerating instrument approach task; reference 2 describes research into the problem of VTOL aircraft hover and low-speed operations during reduced visibility conditions. The investigation described herein extends the experimental approaches of references 1 and 2 to the Army's requirement for attack and scout helicopter missions conducted at night and in adverse weather.

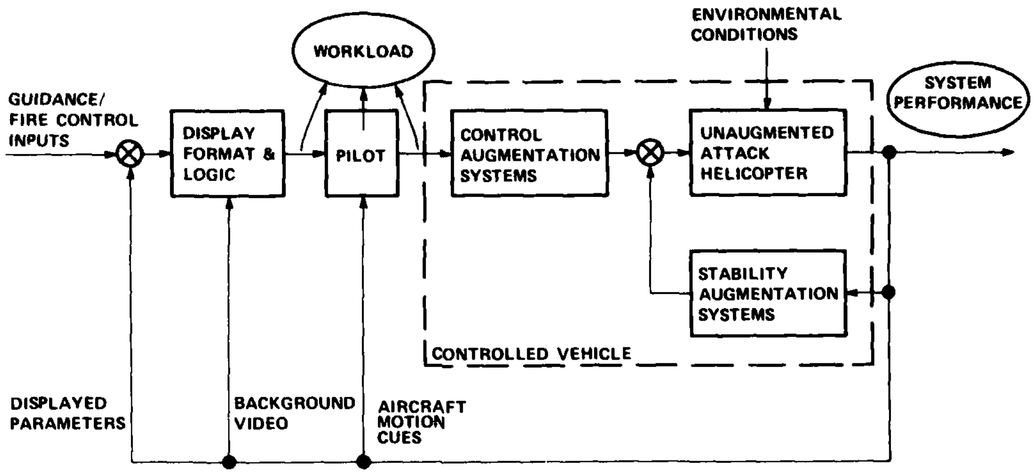

Figure 1.– Control/display system for advanced helicopter.

The design of the present experiment was influenced by previous studies in which the high workload inherent in the low-speed, low-altitude portion of nighttime attack/scout helicopter missions was addressed. One display-oriented concept, evaluated at length in both simulator and flight tests by the Army Avionics Research and Development Activity (AVRADA), consists of the display of flight information superimposed on the video output from a forward-looking infrared (FLIR) sensor; the combined imagery has been presented both on a panel-mounted display with a fixed FLIR sensor and on a helmet-mounted display (HMD) with the FLIR sensor slaved to the motions of the pilot's head (ref. 3). The HMD version of this concept has been adopted as a requirement for the Army's Advanced Attack Helicopter (AAH) Pilot Night Vision System (PNVS) (ref. 4). Preliminary simulations of a system similar to the PNVS conducted by AVRADA revealed that a high workload condition existed during the bob-up maneuver (in which the pilot attempts to maintain a precise hover position over the ground during vertical unmasking and remasking) even though no additional tasks, such as those related to target search and acquisition, were required of the pilot. As a result, it was recommended that the potential benefits of alterations in the dynamics of the hover symbology and/or the implementation of automatic hover augmentation in the aircraft control system be investigated. The design of the experiment described in this paper incorporated those recommendations into a more general investigation of control system and display effects on aircraft handling qualities for an attack helicopter mission that included a weapon delivery task.

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EXPERIMENT DESIGN

As a result of a 1969 agreement between NASA and the Army, the Army's Aeromechanics Laboratory, which is collocated with the Ames Research Center (ARC), has access to ARC research facilities for the purpose of conducting investigations of aerodynamics, rotor system and aircraft dynamics, flight controls and displays, guidance and navigation, and acoustics of rotary wing aircraft.

The experiment reported here was conducted on ARC's six-degree-of-freedom moving-base simulator facility, designated S.01. The simulator cab, which was modified to include a typical helicopter instrument panel and controllers (fig. 2), was integrated with other simulation support facilities as indicated in figure 3. A key element of the simulation was the representation of a helmet-mounted display (HMD) image; the image was presented to the pilot on a panel-mounted TV monitor located so that it reproduced the actual HMD field of view characteristics: an arc, subtended at the pilot's eye, of 30° vertically and 40° horizontally (fig. 4). The black and white image consisted of flight control and fire-control symbology superimposed on the video from a simulated forward-looking infrared (FLIR) sensor mounted on the chin of the aircraft. The simulated FLIR imagery was derived from the camera and terrain board visual system; the scaled terrain used for this experiment is a 400:1 model representative of the Army's Ft. Hunter-Liggett facility.

As indicated in figure 1, it was expected that several elements of the pilot-controlled vehicle-display system would interact to determine the workload required of the pilot to attain a given level of performance for the task in question. Accordingly, three sets of experimental variables were selected for investigation in the simulation program:

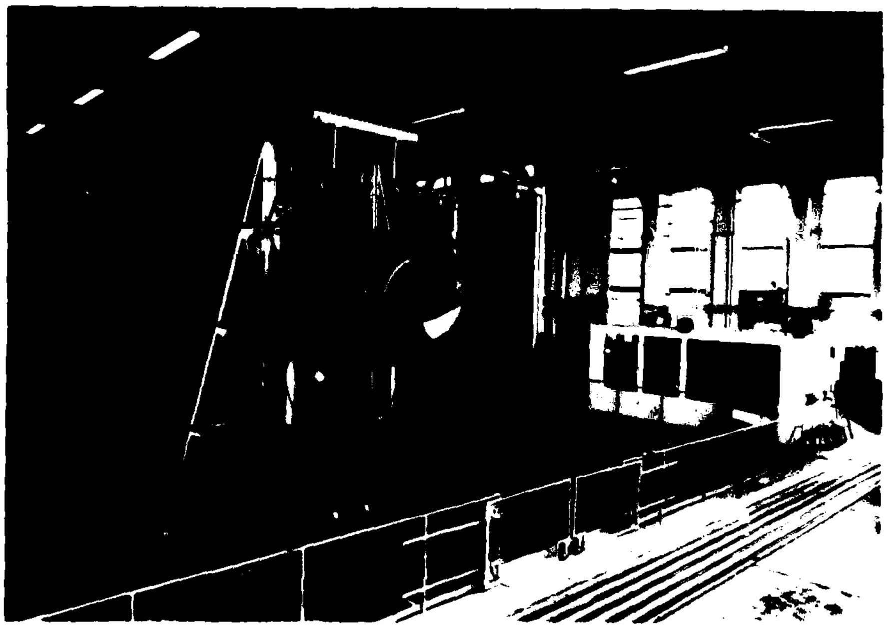

Figure 2.– NASA-ARC S.01 simulator.

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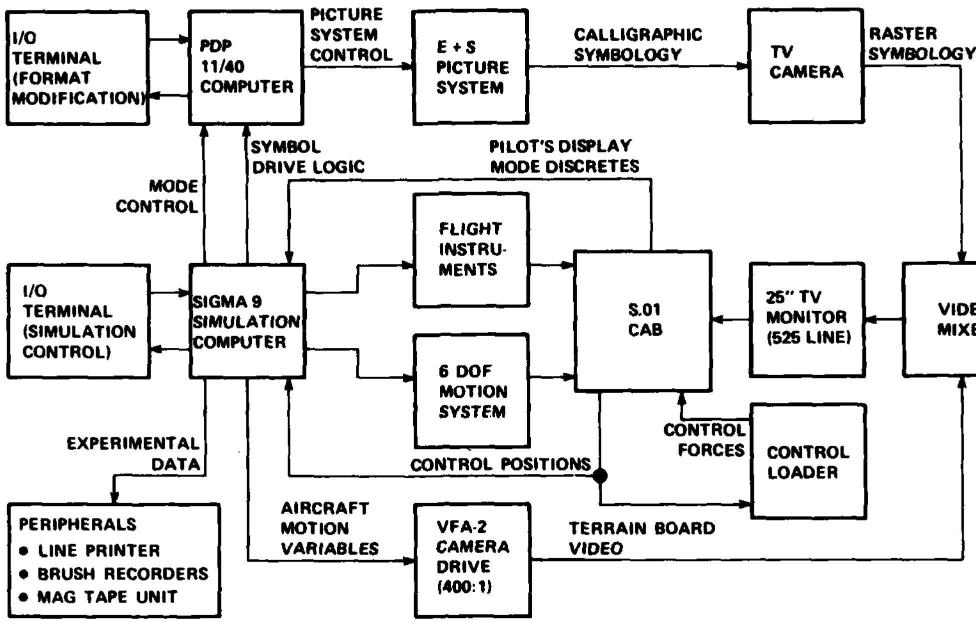

Figure 3.— Simulator systems.

1. Control system – varying degrees of stability and control augmentation, including control system failures.
2. Display – variations in both the format, that is, the location and physical characteristics of the symbols, and in the logic that drives certain key symbols (and thus determines the dynamics of these symbols in response to pilot control and external inputs such as turbulence).
3. Environment – variations in environmental conditions consisting of steady wind, wind shear, and turbulence.

Control Systems

For this experiment, the mathematical model of the unaugmented attack helicopter consisted of six-degree-of-freedom aircraft equations of motion. The equations included a simplified representation of the aerodynamic forces and moments based on both computer-generated and flight-test data for the AAH. No rotor system dynamics were included. The stability and control augmentation systems (SCAS) investigated include two systems specific to the AAH and several hover augmentation system (HAS) concepts designed for the hover and low-speed portion of the mission. Details of the model and the actual implementation of these control systems for the simulation are discussed in reference 5. The resultant generic controlled vehicle characteristics in hover are summarized in table 1.

The control systems presented in table 1 are arranged in an order that is associated with expected reductions in pilot workload for a precision hover task performed under visual meteorological conditions; that is, they are listed in order of increasing ease of hover position control, which is a dominant parameter that determines system performance. Relatively simple SCAS configurations for the AAH

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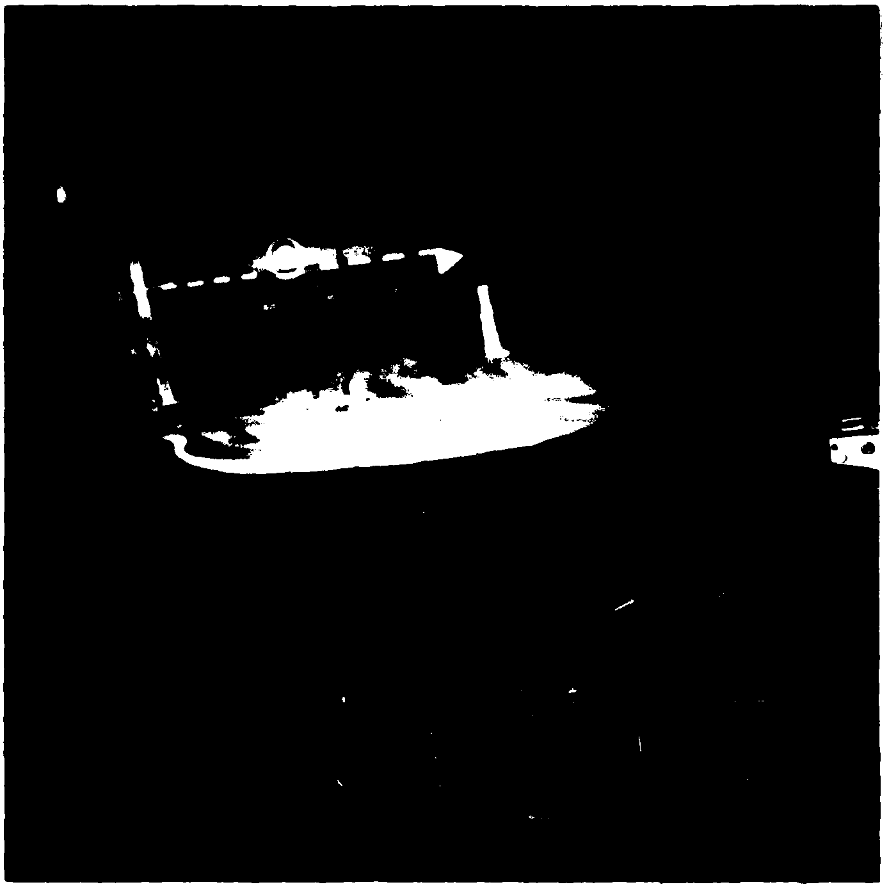

Figure 4.– S.01 cockpit arrangement.

are listed first; they provide the pilot with short-term pitch and roll-rate command and long-term attitude command through the cyclic stick. For a helicopter in hover, a pitch attitude change corresponds to a short-term change in linear acceleration; therefore, a pitch-rate command system in essence places the pilot three integrations away from the desired change in longitudinal position. In order to achieve a satisfactory level of performance with this system, the pilot must be provided with high quality, easily interpretable information on the results of those integrations, that is, pitch attitude, longitudinal inertial velocity, and longitudinal position. Under visual flight conditions, the real world is the source of the required information, however, at night or under reduced visibility conditions, the required information must be obtained, at least in part, from the cockpit instruments and displays. In contrast, the more sophisticated configurations, such as HAS 3, provide the pilot with a controlled vehicle that responds to a longitudinal cyclic stick input with the commanded longitudinal inertial velocity and holds the resulting longitudinal position when the stick is released. This particular system places the pilot only one integration away from

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TABLE 1.– GENERIC CHARACTERISTICS OF CONTROLLED VEHICLE-HOVER

Control system	Controlled axis: Pitch	Roll	Yaw	Collective
AAH SCAS	Quickened pitch attitude command	Quickened roll attitude command	Yaw rate damping augmentation with quickened control response	Unaugmented
AAH Attitude Hold	Pitch attitude command	Roll attitude command	Pseudo-heading hold	Unaugmented
HAS 1	Longitudinal inertial acceleration command, velocity hold	Lateral inertial acceleration command, velocity hold	Yaw rate command, heading hold	Unaugmented
HAS 2	Longitudinal inertial velocity command	Lateral inertial velocity command	See HAS 1	Unaugmented
HAS 3	Longitudinal inertial velocity command, position hold	Lateral inertial velocity command, position hold	See HAS 1	Unaugmented
Vertical Augmentation 1	HAS 2 or HAS 3 characteristics			Altitude rate command
Vertical Augmentation 2	HAS 2 or HAS 3 characteristics			Altitude rate command, altitude hold

the desired position change and, as a result, may reduce the mental workload required for satisfactory performance.

The hierarchy of control systems presented in table 1 is in general dependent on the task that the pilot-vehicle system is expected to perform. Specifically, the various hover augmentation systems have been designed to assist the pilot in reaching and maintaining a precision hover. It is important to realize that the ranking of these control systems when applied to other tasks will likely change drastically; for example, the SCAS is designed to enhance aircraft agility and may therefore be preferable for the higher speed maneuvering flight required for some nap-of-the-earth missions.

In addition to an evaluation of the AAH control systems and the various HAS concepts of table 1 for the nighttime mission, the effects of degraded SCAS modes were also investigated. Specifically, total failures of each of the AAH SCAS axes – pitch, roll, and yaw – were simulated. Finally, a full SCAS failure, resulting in a controlled vehicle with the characteristics of the unaugmented attack helicopter, was implemented.

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Displays

One function of the pilot's display during the nighttime attack helicopter mission is to compensate for the lack of external visual cues. It has been demonstrated that a helmet-mounted display that consists only of a limited field-of-view FLIR image of the outside world is insufficient for the low-speed, low-altitude portion of the mission and that superimposed flight control symbology can considerably enhance the usefulness of this particular display medium (ref. 3). From the pilot's point of view, three display characteristics determine the suitability of a given set of superimposed symbols for a particular task:

1. Information content – Is the displayed information inadequate, sufficient, or excessive for the task?
2. Format – Do the location and physical characteristics of the individual symbols enhance or degrade the efficiency of information transfer?
3. Logic – Do the symbols accurately reflect aircraft status, and do they respond in an orderly fashion to pilot control inputs and external disturbances?

These sets of display characteristics formed the basis for the display variations considered in this experiment.

The baseline display format that was investigated (ref. 4) consists of four discrete display modes – cruise, transition, hover, and bob-up – selectable by the pilot. Reference 3 describes the operational requirements associated with each display mode as (1) cruise – high-speed level flight enroute to the forward edge of the battle area; (2) transition – low-speed, nap-of-the-earth maneuvers, such as dash, quick stop, and sideward flight; (3) hover – stable hover with minimum drift; and (4) bob-up – unmask and remask maneuvers over a selected ground position. The bob-up mode of the baseline format is depicted in figure 5.

In order to explain more clearly the information content and details of the baseline symbology, the symbols are divided into three categories: central (fig. 6), peripheral (fig. 7), and fire control (fig. 8). The central symbology changes as a result of display mode switching; the characteristics of the four display modes are (1) cruise – velocity vector, cyclic director, and hover position symbols deleted; (2) transition – horizon line and hover position symbols deleted; (3) hover – horizon line deleted and hover position symbol fixed at center, velocity vector sensitivity increased compared to transition mode; and (4) bob-up – horizon line deleted, hover mode velocity vector sensitivity retained.

H_0, H_1 FORMAT

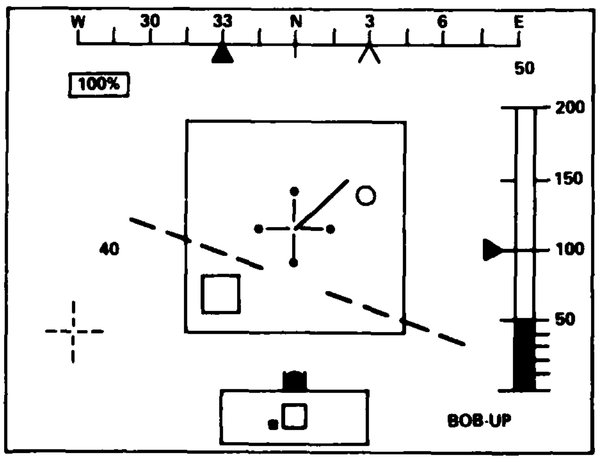
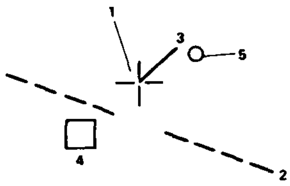
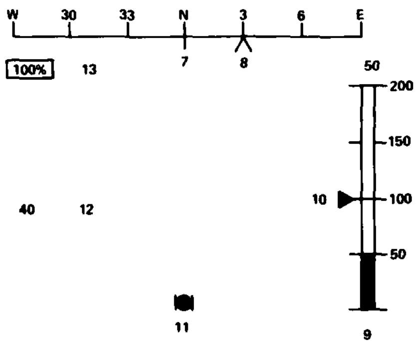


Figure 5.– Baseline display format.



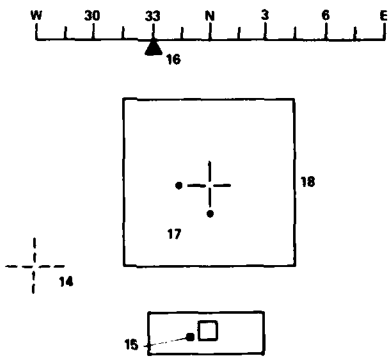
SYMBOL	INFORMATION
1. Aircraft reference	Fixed reference for horizon line, velocity vector, hover position, cyclic director, and fire control symbols
2. Horizon line (cruise mode only)	Pitch and roll attitude with respect to aircraft reference (indicating nose-up pitch and left roll)
3. Velocity vector	Horizontal Doppler velocity components (indicating forward and right drift velocities)
4. Hover position	*Designated hover position with respect to aircraft reference symbol (indicating aircraft forward and to right of desired hover position)*
5. Cyclic director	Cyclic stick command with respect to hover position symbol (indicating left and aft cyclic stick required to return to designated hover position)

Figure 6.– Central symbology.



SYMBOL	INFORMATION
7. Aircraft heading	Moving tape indication of heading (indicating North)
8. Heading error	Heading at time bob-up mode selected (indicating 030)
9. Radar altitude	Height above ground level in both analog and digital form (indicating 50 ft)
10. Rate of climb	Moving pointer with full-scale deflection of ±1,000 ft/min (indicating 0 ft/min)
11. Lateral acceleration	Inclinometer indication of side force
12. Airspeed	Digital readout in knots
13. Torque	Engine torque in percent

Figure 7.– Peripheral symbology.



SYMBOL	INFORMATION
14. Cued line of sight	Overlays designated target position on background video when target is in display field of view
15. Coarse target location	Designated target position with respect to display field of view (inner rectangle) and sensor limits (outer rectangle)
16. Target bearing	Designated target bearing (indicating 330° or 30° to left of current heading)
17. Target location dots	Illumination of two adjacent dots indicates display quadrant in which designated target is located
18. *Missile launch constraints*	*Limits with respect to aircraft reference for successful weapon lock-on to designated target*

Figure 8.– Fire-control symbology.

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Effects of variations in displayed information content, format, and logic were investigated by alterations to the hover and bob-up modes of this baseline format.

Variations in information content were mechanized in the form of the following display failures: FLIR failure – loss of background video; loss of velocity vector symbol; loss of cyclic director symbol; loss of velocity vector and cyclic director symbols; and loss of all hover symbols – velocity vector, cyclic director, and hover position symbols inactive.

To explore the effects of variations in the display format, an alternative format, consisting of potential improvements to the baseline format, was implemented (fig. 9). The separation of the horizontal status and command information (fig. 6) from the vertical status information located on the right side of the display (fig. 7) was judged to be a possible deficiency in the baseline format. Concentration on the central symbols could result in degraded altitude tracking performance because of (1) the lack of vertical-horizontal information integration, (2) the incompatibility of the location of the vertical information with the location of the pilot's primary vertical controller (the collective pitch control) located on the pilot's left side, and (3) the lack of vertical command information. The first of these possible deficiencies was not addressed for this experiment. As a potential solution to the latter two deficiencies, the alternative format includes the radar altitude information on the left-hand side and, in lieu of a rate-of-climb indicator, a collective control director driven by blended altitude and altitude rate information; when positioned on the desired value of displayed altitude by the pilot's collective control inputs, the collective control director causes the aircraft to reach and maintain that altitude. This format also includes a horizon line – which remains on the display in all four modes to provide a compelling display of aircraft attitude in hover – and an analog display of low-range airspeed.

Possible display deficiencies associated with the logic driving the central hover symbols were also identified. In reference 3, a relatively noise-free estimate of the horizontal inertial velocity components is derived for use in driving the velocity vector symbol of the baseline display (fig. 6). This estimate involves the complementary filtering of low-frequency Doppler velocity with high-frequency estimates of inertial velocity based solely on aircraft attitude. Improvements in the accuracy of this estimated velocity were obtained by changing filter characteristics and by including linear accelerometer data in the high-frequency velocity estimate. In addition, the sensitivities of the baseline hover symbology – velocity vector, cyclic director, and hover position – documented in reference 3 were altered, using classical manual control theory, to be compatible with the controlled

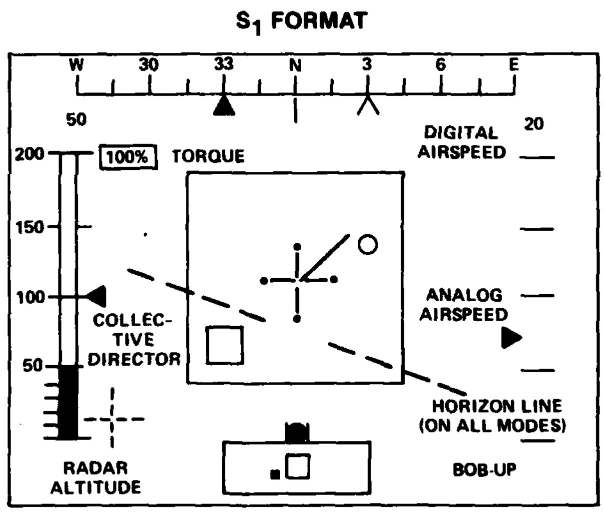

Figure 9.– Alternative display format.

vehicle characteristics. As a result, the sensitivity of the cyclic director symbol varied, in general, with the control system characteristics (table 1).

The investigation of these three display areas of interest resulted in the following three basic display variations:

1. H_0 – baseline display format (figs. 5–8); reference 3 hover symbology logic
2. H_1 – baseline display format; revised inertial velocity estimate; sensitivity of hover symbology based on classical manual control theory; five display failure modes
3. S_1 – alternative display format (fig. 9); H_1 display logic

Environment

To provide a more realistic environment for the simulation and to assess the effects of external disturbances, a model of low-altitude wind and turbulence was implemented for the simulation (ref. 5). Two levels of disturbances were investigated: (1) calm – no wind or turbulence, and (2) moderate – a 10-knot steady wind at the nominal altitude, a moderate wind shear with altitude, and 3.4 ft/sec rms vertical and 6.8 ft/sec rms horizontal gusts.

EXPERIMENT

Three pilots served as evaluation pilots for the experiment: Pilot A, an Army experimental test pilot with 3,165 flight hours, 2,450 of which are in rotary wing aircraft (~90 evaluations); Pilot B, an experimental test pilot with 4,800 flight hours, 2,700 of which are in rotary wing aircraft (~12 evaluations); and Pilot C, a NASA aerospace engineer and pilot with 7,700 flight hours, 1,160 of which are in rotary wing aircraft (~30 evaluations).

The evaluation task for this investigation consisted of several segments of the primary attack helicopter mission. These segments and the corresponding display modes follow:

1. Cruise: accelerate to an airspeed (V) of 40 knots at 100 ft above ground level (AGL).
2. Transition: descend to 50 ft AGL and decelerate to a hover near a designated point on the terrain.
3. Hover: hover between 0–50 ft AGL.
4. Bob-up: bob-up to 100 ft AGL over designated hover position.
5. Bob-up: conduct target search in azimuth; when target designated, bring target within the missile launch constraints and simulate missile launch.
6. Bob-up: descend to original hover position.
7. Transition-hover: accelerate to V = 40 knots and depart the area.

Most of the evaluations were performed for an abbreviated task that comprised segments 3–6 above. Each evaluation consisted of two runs of either the full mission or the hover and bob-up task. For each run, system performance data, such as hover position accuracy and attitude and velocity excursions, and pilot physical workload data, in the form of control activities, were collected. At the end of each evaluation the pilot was asked to assign a numerical Cooper-Harper pilot rating (ref. 6) for the task from the scale of figure 10 and to provide commentary, based on a pilot commentary guide, to assist the experimenter in identifying the areas that most heavily influenced the rating.

The Cooper-Harper pilot rating (PR) is commonly used in aircraft handling qualities research and is the basis for the handling qualities "Levels" used in specifications for military aircraft (e.g., ref. 7). The rating scale of figure 10 emphasizes the interdependence of system performance and pilot workload in the dichotomous decisions required of the evaluation pilot for the selection of a numerical rating.

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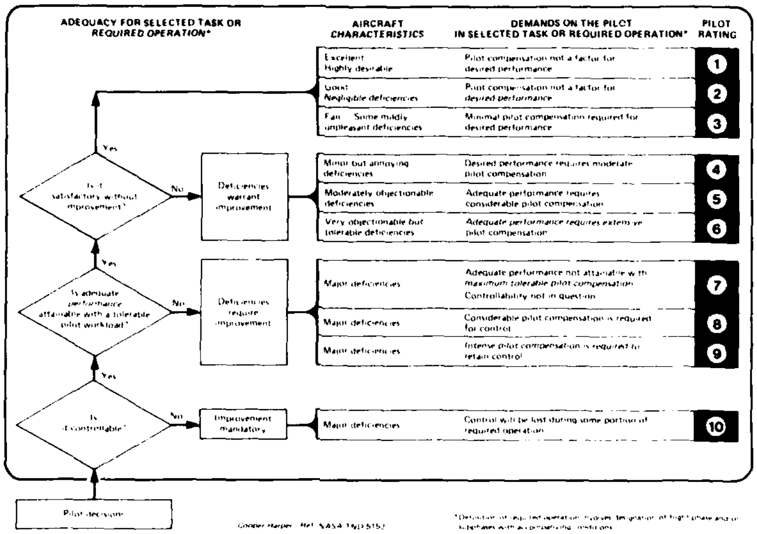
HANDLING QUALITIES RATING SCALE



DEFINITIONS FROM TN-D-5153

COMPENSATION

The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics

HANDLING QUALITIES

Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role

MISSION

The composite of pilot-vehicle functions that must be performed to fulfill operational requirements May be specified for a role complete flight, flight phase or flight subphase

PERFORMANCE

The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task (*Pilot vehicle performance* is a measure of handling performance Pilot performance is a measure of the *manner* or efficiency with which a pilot moves the principal controls in performing a task)

ROLE

The function or purpose that defines the primary use of an aircraft

TASK

The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment

WORKLOAD

The integrated physical and mental effort required to perform a specified piloting task

Figure 10.– Cooper-Harper pilot rating scale.

Specifically, a "controllable" control/display combination may be assigned a numerical rating that places it in one of the three primary performance-workload categories, or handling qualities "Levels" (ref. 6):

1. Level 1 ($1 \leqslant PR \leqslant 3$): Desired, or at least clearly adequate, performance for the task is attainable with a satisfactory level of pilot workload.
2. Level 2 ($4 \leqslant PR \leqslant 6$): Desired performance is not necessarily obtained; however, adequate performance is attainable with pilot compensation, that is, increased workload, up to the maximum tolerable level.
3. Level 3 ($7 \leqslant PR \leqslant 9$): Adequate performance is not attainable with maximum tolerable pilot workload; an excessive workload level would be required for adequate performance.

Thus, the pilot evaluation data – the ratings and commentary – gathered for this experiment are an important source of information regarding the interdependence and necessary tradeoffs of system performance and pilot workload.

The analysis of the pilot evaluation data is complete, and a summary is presented below. An analysis of the quantitative performance and workload data is in progress.

RESULTS

Figure 11 shows the pilot rating results from pilot A for the primary experimental matrix. It demonstrates that, for the hover and bob-up task with moderate wind and turbulence, the baseline control-display configuration (SCAS/H_0) is rated as being unsatisfactory without improvement and approaches Level 3 handling qualities. Improvements in the pilot's ratings are obtained both by control system modifications (e.g., Attitude Hold/H_0) and by the alterations to the velocity vector logic and hover symbology scaling (SCAS/H_1). However, no further improvements occur as a result of the display format modifications (SCAS/S_1). The H_1 display with either the Attitude Hold feature or the two velocity command control systems (HAS 2 and 3) provides adequate but still unsatisfactory (Level 2) systems for the task. Vertical augmentation together with a horizontal velocity command system is required for a satisfactory pilot rating (Level 1).

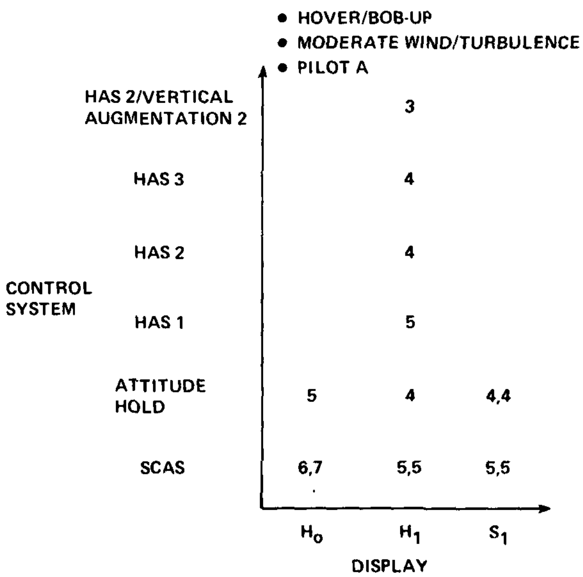


Figure 11.– Pilot rating data – primary configuration matrix.

Figure 12 demonstrates a general degradation of pilot rating with control system and display failures. The improvement in pilot rating for the FLIR failure is attributed, according to pilot commentary, to the improvement of the quality of the symbology with the resultant uniform video background. The hover/vertical augmentation system improved the pilot rating for each of the display failures investigated, never allowing the handling qualities to fall below

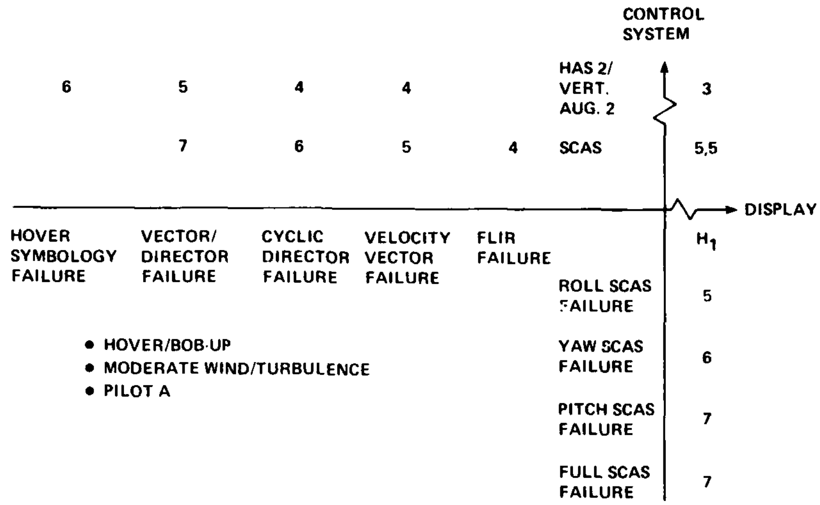


Figure 12.– Pilot rating data – failure effects.

Level 2. The pitch SCAS and full SCAS failures result in Level 3 handling qualities as does the loss of the velocity vector and cyclic director with the SCAS fully functional.

No system was found to have Level 1 handling qualities for the full mission; the need for maneuverability during the higher speed flight segments degraded the ratings assigned to the more heavily-augmented control systems. The lack of turbulence generally improved pilot ratings for the less-heavily augmented control systems – the SCAS/H_1 and SCAS/S_1 combinations received pilot ratings of 3 for the hover/bob-up task. Finally, interpilot variations were only significant for the two AAH control systems and the control system failures; for example, pilot C rated the SCAS/H_1 combination as a 7 for the hover and bob-up task in turbulence, that is, Level 3 handling qualities; pilot B rated the same configuration as a 4.

For most of the evaluations, especially those conducted in turbulence, the pilot commentary indicates that the division of attention among horizontal position control, altitude control, and target acquisition during the hover and bob-up was crucial to their ratings.

CONCLUSIONS

The following conclusions are based on the handling qualities results obtained from the piloted simulator evaluations:

1. The baseline control-display system is unsatisfactory for the task evaluated and requires improvement.

2. Improvements to the baseline system may be achieved by modifying either the control system or display.

3. The display modifications that most significantly improve pilot ratings are the increased accuracy of the velocity vector symbol drive logic and the rescaling of the hover symbology based on the

characteristics of the controlled vehicle; the variations in display format investigated provided no significant improvements. The information content of the baseline display format is satisfactory for the task.

4. A horizontal velocity command system and artificial augmentation of the collective axis are required for satisfactory handling qualities during hover and bob-up in moderate turbulence.

5. A failure of the baseline pitch SCAS, even with the improved hover symbology dynamics, makes the system inadequate for the task. With the baseline SCAS, a failure of the hover symbols also results in an inadequate system; a hover and vertical augmentation system with the same display failure results in a system that is adequate but still unsatisfactory for the task.

In general, the single-mode SCAS represented by the baseline system is unsatisfactory for the entire nighttime attack helicopter mission; the requirements for the hover, bob-up, and weapon delivery tasks are sufficiently different from those for the higher speed flight tasks that widely different controlled vehicle characteristics are necessary for these mission segments for a satisfactory system overall. Finally, the dynamics of the central hover symbols of the pilot's display must be designed to be compatible with the dynamic characteristics of the controlled vehicle to ensure pilot acceptability.

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